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Inventors: Mark Bashkansky et al.

Patent Application  
Navy Case No. 78,316

1                   RAPID, HIGH-RESOLUTION SCANNING OF FLAT AND  
2                   CURVED REGIONS FOR GATED OPTICAL IMAGING

3                   BACKGROUND OF THE INVENTION

4       1.   Field of the Invention

5           The present invention relates to optical scanning and  
6           particularly to the use of special scanning techniques wherein  
7           high resolution near-surface images can be acquired rapidly in  
8           either a flat or a curved surface geometry.

9  
10       2.   Description of the Related Art

11           It has been previously demonstrated that ultrafast optical  
12           gating techniques can be used for defect detection in advanced  
13           ceramic materials. One of the most promising techniques, due to  
14           its low cost and ease of implementation, is optical coherence  
15           tomography (OCT). This technique is based on low coherence fiber  
16           interferometry and can produce high resolution subsurface images.  
17           However, to make devices based on OCT practical, the image  
18           acquisition time should be fast (hopefully approaching video  
19           rates). This was recognized and an OCT technique was modified so  
20           that the image acquisition time was reduced to ~ 300 msec. This  
21           was accomplished at a price of reduced spatial resolution since  
22           the scattered light was not always collected at the focus of the  
23           lens. Another disadvantage of this technique is that the image  
24           is always collected in the X-Z plane, where Z represents the  
25           depth into the sample and X represents one transverse dimension.

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1                                    SUMMARY OF THE INVENTION

2            Accordingly, an object of the present invention is to  
3    provide an improved scanning device.

4            Another object of the invention is to apply special optical  
5    scanning methods to improve optical techniques used for detecting  
6    scattered laser radiation from near-surface structures, defects,  
7    or imperfections in ceramic and other translucent, but highly  
8    scattering materials.

9            Another object of the invention is to provide an improved  
10   scanning device wherein the improvements are achieved by reducing  
11   image acquisition time while keeping spatial resolution high for  
12   various surface topologies.

13           Another object of the invention is to provide a scanning  
14   device which produces a two-dimensional line scan of a sample and  
15   maintains a constant optical path length during the entire scan.

16           A further object of the invention is to provide an improved  
17   scanning device which uses special scanning techniques so that  
18   high resolution near-surface images can be acquired rapidly in  
19   either a flat or a curved surface geometry.

20           These and other objects of the invention are achieved by  
21   providing an optical scanning system for developing high-  
22   resolution, near-surface images of a sample by reducing image  
23   acquisition time while keeping spatial resolution high for  
24   various surface topologies. By using special scanning techniques,

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1 high resolution near-surface images can be acquired rapidly in  
2 either one or two dimensions in either a flat or a curved surface  
3 geometry with a constant optical path length.

4  
5 BRIEF DESCRIPTION OF THE DRAWINGS

6 These and other objects, features and advantages of the  
7 invention, as well as the invention itself, will become better  
8 understood by reference to the following detailed description  
9 when considered in connection with the accompanying drawings  
10 wherein like reference numerals designate identical or  
11 corresponding parts through the several views and wherein:

12 FIG. 1 shows a standard scanning technique for a single scan  
13 in one dimension of a plane;

14 FIG. 2 shows a 4-f lens system which allows scanning in a  
15 linear direction from collimated beam to collimated beam;

16 FIG. 3 is a three-dimensional representation of FIGs. 1  
17 and 2 combined to show scanning in both the X and Y scan  
18 directions onto a flat plane, keeping the optical path length  
19 constant;

20 FIG. 4 shows a technique for performing a linear scan along  
21 a spherical concave surface with a constant optical path length  
22 along that concave surface; and

23 FIG. 5 shows a technique for performing a linear scan along  
24 a spherical convex surface, with a constant optical path length

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1 along that convex surface.

2  
3 Detailed Description of the Preferred Embodiments  
4

5 The purpose of this invention is to improve on the  
6 previously reported OCT techniques by providing a special optical  
7 scanning arrangement, in combination with fast PZT modulation in  
8 the reference or the signal arm of the interferometer, such that  
9 high resolution images may be acquired rapidly in a flat or  
10 curved surface topology either parallel or perpendicular to the  
11 surface. The improvement results in a practical device capable  
12 of obtaining images in a flat or curved topology, parallel or  
13 perpendicular to the surface, rapidly and with high resolution.  
14 Additionally, three-dimensional surface profiling can also be  
15 accomplished on curved surfaces without gating, in a scanning  
16 confocal microscope configuration.

17 In typical OCT the pathlength between the reference and  
18 signal beams in the reference and signal arms of the  
19 interferometer is rapidly varied to produce a Doppler shift  
20 between the beams. If the sample is moved to accomplish this,  
21 then the return signal always originates in the focus of the  
22 collecting lens. However, the sample in general can only be  
23 moved with a mechanical translation stage, which limits the image  
24 collection time to  $> 10$  seconds. Furthermore, the images can

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1 only be acquired perpendicular to the surface. A technique used  
2 in the prior art reduced the image collection time to ~ 300 msec.  
3 This was accomplished by stretching an optical fiber in the  
4 reference arm by approximately 3 mm with a PZT. However, this  
5 has the side effect of moving the gating depth through the focus  
6 of the image collecting lens. The waist size of a Gaussian beam  
7 is given by the following equation:

$$w_z^2 = w_0^2 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2 \right]$$

8  
9 where  $W_z$  is the beam waist size as a function of depth  $Z$ ,  $W_0$  is  
10 the minimum beam waist size and  $\lambda$  is the wavelength. Using this  
11 equation at a wavelength of 1  $\mu\text{m}$  the beam size has to be at least  
12 30  $\mu\text{m}$  to have no significant increase in size over a depth of  
13 3mm. This method therefore greatly limits the possible spatial  
14 resolution and restricts the scans to depth cross-sections.

15 The purpose of this invention is to improve on these typical  
16 OCT techniques in a number of ways. In order to enable optical  
17 scanning of the signal beam, the modulation of the signal must be  
18 separated from the motion of either the sample or the light  
19 beams. This is accomplished by winding a length of fiber on a  
20 special high speed-low voltage PZT and changing the fiber length  
21 by only ~ 3 wavelengths. Besides achieving very high modulation  
22 frequencies (> 300kHz), this also separates the modulation from

1 any translation of the sample and enables optical scanning in any  
2 direction. The focus of the scan can now be scanned with fast,  
3 commercially available galvanometer mirrors in such a way that  
4 the focal size does not change and the total optical path length  
5 (OPL) from the signal fiber output to the focus stays constant.  
6 If this condition is satisfied, then the gated image will contain  
7 the scanned area at the best possible resolution. Three scanning  
8 techniques of interest have been identified, which will now be  
9 discussed by referring to the drawings.

10  
11 1. A plane at any angle to the surface using one optical  
12 scanner.

13 FIG. 1 shows a schematic diagram of a scanning system or  
14 arrangement wherein an optical fast scan is performed in one  
15 dimension parallel to the surface, while a slower motion is  
16 performed in the other two dimensions by mechanical translation  
17 stages.

18 The scanning system of Fig. 1 is a focused scanning system  
19 which allows a collimated light beam to be focused and scanned in  
20 one dimension. As will be explained, the scanning system or  
21 arrangement in FIG. 1 is used to focus a collimated light beam,  
22 such as a laser beam, to a spot on a sample by rotating the  
23 collimated part of the beam before it reaches the lens. That  
24 scanning can be accomplished in a straight line and the focus  
25 will move on a planar surface in that straight line.

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1       The scanning system of FIG. 1 includes a scanner 11  
2       comprising a rotating scanner (not shown) and a scanner mirror  
3       (not shown) attached to and rotated by the rotating scanner, a  
4       flat field lens 13 and mechanical translation stage 15. The  
5       scanner 11 can be a galvanometer which includes the scanner  
6       mirror. The flat field lens 13 is a focusing lens.

7       An input collimated signal light beam 17 from some  
8       collimated light source (not shown) incident on the center of the  
9       mirror of the scanner 11 is reflected by the mirror through the  
10      focusing lens 13. The lens 13 focuses the collimated light beam  
11      to a spot one focal length ( $1-f$ ) away on a sample 19. The scanner  
12      11 is rotated by any suitable means (such as a shaft in an  
13      exemplary galvanometer - not shown) in the directions shown by  
14      double arrows 21 to produce a linear scan across the sample 19.  
15      The mechanical translation stages 15 move the sample in the other  
16      two dimensions by means well known in the art.

17      In operation, when the distance from the center of a  
18      scanning galvanometer mirror on the scanner 11 to the flat field  
19      lens 13 is equal to the focal length of the lens 13, the input  
20      light beam 17 will scan a flat line parallel to the surface of  
21      the sample 19 in the focal plane of the lens 13 without changing  
22      the OPL. A flat field lens 13 is designed to keep the focus at a  
23      minimum in this arrangement. However, even though the beam 17 is  
24      collimated, it has to be at the center of the scanning mirror of



1 the scanner 11 for constant OPL. This is different than the  
2 requirement for confocal scanning microscopy, where only the  
3 focus position is important and not the OPL.

4  
5  
6 2. A plane parallel to the surface using two optical  
7 scanners.

8 To enable even faster scanning in the plane parallel to the  
9 surface, as in confocal scanning microscopy, a different system  
10 or arrangement is required. The simple scanning system used in  
11 confocal scanning microscopy cannot be adapted because the OPL is  
12 not constant during the scan. Therefore, a second scanning  
13 system, shown in FIG. 2, is utilized together with the scanning  
14 system shown in FIG. 1 to enable fast gated scanning in a plane.

15 FIG. 2 shows the optical arrangement, including a second  
16 scanner 25, similar in structure and operation to the scanner 11  
17 in FIG. 1. The scanner 25 has to be used to keep a constant path  
18 length for a light beam, when utilized with the first or focusing  
19 scanning system of FIG. 1, to make a two-dimensional line scan  
20 and keep the optical path length constant during that entire two-  
21 dimensional line scan. More specifically, FIG. 2 shows a  
22 transverse dimension and the scanning within that transverse  
23 dimension which, when combined with the system of FIG. 1, allows  
24 a complete two-dimensional scan across a flat surface. In other  
25 words, FIG. 2 shows the optical arrangement that must be used to

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1 keep the optical path length constant for that second dimension  
2 of scanning.

3 In FIG. 2, a 4-f lens system 27 and 29 is used together with  
4 a scanning galvanometer mirror in the scanner 25, in the  
5 dimension perpendicular to that used in FIG. 1, to produce fast  
6 scanning in two dimensions. In the arrangement shown in FIG. 2,  
7 the OPL stays constant throughout the scan, while the scan is  
8 performed always in the focus of the lens 13 in FIG. 1.

9 In the operation of the system of FIG. 2, a collimated light  
10 beam 31, which is incident on and reflected from the scanning  
11 mirror in the scanner 25, is scanned across the face of a flat  
12 field lens 27. A second flat field lens 29 is also located in  
13 the 4-f lens arrangement. Both the first and second  
14 flat field lenses 27 and 29 are similar in operation to the flat  
15 field lens 13 in FIG. 1.

16 In the 4-f lens arrangement of FIG. 2, the lens 27 is  
17 located one focal length ( $1-f$ ) away from the scanner 25, the  
18 distance between lenses 27 and 29 is two focal lengths ( $2-f$ ), and  
19 the distance between the lens 29 and the point of combination  
20 with the scanner 11 in FIG. 1 (to be explained in FIG. 3) is one  
21 focal length ( $1-f$ ) away. Thus, in FIG. 2 there are four focal  
22 lengths ( $4-f$ ) distance between the scanner 25 in FIG. 2 and the  
23 scanner 11 in FIG. 1, which would be combined with the light  
24 output of FIG. 2. (To be explained in FIG. 3.)

1       The flat field lens 13 in FIG. 1 and the two flat field  
2       lenses 27 and 29 in FIG. 2 are all focusing lenses, arbitrary in  
3       size, and are designed to have a minimal aberration when they are  
4       used to focus collimated light down to a focal spot at one focal  
5       length ( $1-f$ ) away from the lenses. For example, the lens 27  
6       focuses the light beam 31 down to a focal spot 33 which is  
7       located one focal length ( $1-f$ ) from each of the lenses 27 and 29.  
8

9       FIG. 3 is a three-dimensional representation of the  
10      combination of FIGS. 1 and 2, combined in such a way that two-  
11      dimensional scanning occurs. The scanning occurs along a flat  
12      plane surface, a planar surface, and the focal spot will trace  
13      along that planar surface and the optical path length will stay  
14      constant over that entire scan over that flat surface.

15      As shown in FIG. 3, the structural elements of FIG. 2 are  
16      placed just ahead of the structural elements of FIG. 1 to produce  
17      a combined system which produces a two-dimensional line scan of  
18      the sample 19 while keeping an optical path length constant  
19      during the entire scan over the sample 19.

20      As explained before, the scanner 11, flat field lens 13,  
21      mechanical translation stage 15 (FIG. 1) and sample 19 are the  
22      components from FIG. 1 and operate as explained in relation to  
23      FIG. 1 to focus a light beam and allow that focused light beam to  
24      scan across a sample in one dimension; while the scanner 25, and

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1 flat field lenses 27 and 29 are the components from FIG. 2 and  
2 operate as explained in relation to FIG. 2 to produce a scan in a  
3 second dimension in such a way to keep the optical path lengths  
4 constant along the focus on the sample itself over the entire  
5 scan.

6 In the operation of the system of FIG. 3, the collimated  
7 light beam 31 is incident on the mirror of the rotating scanner  
8 25 and is deflected off of that mirror and passes through flat  
9 field lens 27 which focuses the beam to the focal spot 33. That  
10 beam at the focal spot 33 grows again as it approaches the flat  
11 field lens 29. After it passes through the lens 29, it is in a  
12 collimated state and is deflected off of the scanner 11 (FIG. 1)  
13 to the flat field lens 13 (FIG. 1). The light beam 31 is focused  
14 by the lens 13 before reaching the flat plane of the sample 19  
15 that is to be scanned over.

16 In summary, FIGS. 1, 2 and 3 showed and described the  
17 scanning of a planar surface, with FIG. 1 dealing with a scan in  
18 a first dimension, FIG. 2 dealing with a scan in a second  
19 dimension and FIG. 3 dealing with a scan in both of the first and  
20 second dimensions.

21  
22 3. A spherical convex surface using one optical scanner  
23 and a slower rotating mechanical device.

24 To produce either gated or non-gated confocal scans of  
25 spherical objects such as ball bearings, a special scanning

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1 system is required. As shown in FIG. 4, only a single scanner and  
2 a lens is sufficient to produce a scan of a spherical concave  
3 surface. As depicted in FIG. 4, the focus is tracing a concave  
4 sphere during a scan. This type of scanning is well known and is  
5 used to study various concave objects such as the interior of the  
6 eye.

7 In the operation of the system of FIG. 4, a collimated light  
8 beam 41 is focused by a flat field lens 43 onto a scanner 45  
9 similar to the scanner 11 (FIG. 1) or scanner 25 (FIG. 2) to scan  
10 over a concave surface 47 in one dimension. To scan in two  
11 dimensions, FIG. 4 could be combined with the system shown in  
12 FIG. 2. Such a combination of scanners would produce a linear  
13 scan in one dimension (using FIG. 2) and a scan over a spherical  
14 convex surface in the other dimension (using FIG. 4).

15 Referring now to FIG. 5, FIG. 5 shows a technique for  
16 performing a linear scan along a spherical convex surface, with a  
17 constant optical path length along that convex surface. To  
18 produce a scan of a convex surface, an arrangement different from  
19 that of FIG. 4 is required.

20 In FIG. 5 a flat field lens 52 forms a focus before a  
21 scanner 55. Scanner 55 is similar to scanner 11 (FIG. 1) or  
22 scanner 25 (FIG. 2). The expanding light beam is rotated by  
23 scanner 55 as shown by the double arrows 56. The focus 53 of  
24 light beam 51 that occurs before the scanner 56 is placed one

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1 focal length away from lens 58. Because of the geometry used in  
2 this configuration, it is possible to draw a virtual line that  
3 represents how the focus spot 53 moves as seen by lens 58. That  
4 line is represented by the dotted line 57. In other words,  
5 dotted line 57 describes the motion of the focal spot 53 as seen  
6 by lens 58. The combined distance from the virtual line shown as  
7 the dotted line 57 to the line 61 forms, in combination with  
8 lenses 58 and 59, a 4-f system. The 4-f system includes the  
9 distance from focus 53 to lens 58 (which is the same distance as  
10 from virtual line 57 to lens 58), the distance between lenses 58  
11 and 59, and the distance from lens 59 to line 61. The distance  
12 from the focus 53 to the lens 58 is one focal length, the  
13 distance between lenses 58 and 59 is two focal lengths, and the  
14 distance between lens 59 and line 61 is one focal length, where  
15 the focal lengths of both lenses are the same and equal to  $f$ .

16 Because the combination of virtual line 57, lenses 58 and 59  
17 and line 61 forms a 4-f system, the virtual line 57 will  
18 transform into the convex line 61 in the focus of the lens 59.  
19 This transformation only works in a 4-f lens system. If a single  
20 2f to 2f lens imaging system (not shown) were used instead, the  
21 line 61 traced by the scanning beam 41 would not be spherical.  
22 The explanation for this is based on the observation that a  
23 single lens transforms  $Z$  positions in space asymmetrically from 0  
24 to  $2f$  into positions from  $2f$  to  $\infty$  and vice versa. However, a 4-f

1 two lens system transforms 0 to f positions into f to 2f  
2 positions symmetrically, preserving the spherical nature of the  
3 line 61. The slow scanning in other dimensions can be performed  
4 by mechanical means. The radius of curvature of the convex scan  
5 shown in FIG. 5 can be adjusted by changing the relative position  
6 of focus 53 and scanner 55. Making the distance between focus 53  
7 and scanner 55 large increases the radius of curvature of line  
8 61, and making that distance small decreases the radius of  
9 curvature of line 61. As an example of a scan over a spherical  
10 surface, a prototype device performed a 2x2 mm scan on the  
11 surface of a ball bearing in less than 1 sec.

12 Even though these scanning techniques were developed for  
13 gated optical imaging, they can also be applied for confocal  
14 scanning microscopy on curved and flat surfaces.

#### 15 16 Advantages and New Features of the Invention

17 The above-described implementation of optical scanning  
18 techniques allows fast image acquisition in various surface  
19 topologies while keeping high spatial resolution and while  
20 keeping a constant optical path length during the scan. When  
21 applied to a convex surface, these optical techniques can also  
22 dramatically improve the resolution of images obtained with a  
23 confocal scanning microscope.

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1  
2 Alternatives

3       Aspherical lenses, or other lens combinations may be  
4 designed to improve the focus of the signal beam. Two-  
5 dimensional gated imaging may also be feasible with some other  
6 surface geometry. An optical polarizer may be used in  
7 conjunction with the gating techniques to further reduce noise  
8 due to the surface reflection or to study birefringences of the  
9 sample. Lens pairs in the 4-f imaging system described in FIG. 5  
10 do not have to be of equal focal length. If the focal lengths  
11 are different, but if distances between different elements are  
12 adjusted properly, there is the potential to magnify or reduce  
13 the final radius of curvature over the initial radius of  
14 curvature, while still keeping a convex scan in which the OPL is  
15 constant.

16       Therefore, what has been described in a first preferred  
17 embodiment of the invention is an optical scanning system for  
18 developing high-resolution, near-surface images from a desired  
19 surface topology of a sample, the optical scanning system  
20 comprising: a light source for producing a collimated light  
21 beam; a first optical system for directing the collimated beam to  
22 a first position on a first optical axis; a first scanner device  
23 having a first center portion for scanning the collimated light  
24 beam from the light source through the first optical system to



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1 the first position on the first optical axis with a constant path  
2 length in a first dimension; a second scanner device having a  
3 second center portion for scanning the scanned collimated light  
4 beam from the first portion on the first optical axis along a  
5 second optical axis orthogonal to the first optical axis; and  
6 a second optical system for focusing the collimated light beam  
7 onto the desired surface topology in a second dimension;  
8 the first and second scanner devices cooperatively operating to  
9 cause the collimated light beam to scan the desired surface  
10 topology of the sample with a focused constant optical path  
11 length in both of the first and second dimensions of the sample.

12 In a second preferred embodiment of the invention, a  
13 scanning system for scanning in first and second dimensions a  
14 convex surface of a sample is disclosed. The scanning system  
15 comprises: a light source for producing a collimated light beam;  
16 a scanning mirror having a scanning surface; a first focusing  
17 lens for focusing the collimated light beam before the scanning  
18 mirror; second and third focusing lenses optically aligned with  
19 each other, the combination of the scanning surface of the  
20 scanning mirror, the first, second and third focusing lenses and  
21 the convex surface of the sample forming a 4-f system so that the  
22 focus of the first lens transforms into the convex surface in the  
23 focus of the third focusing lens, the second focusing lens  
24 positioned such that its focus coincides with the on-axis

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1 virtual location of the focused collimated light beam from the  
2 first focusing lens as seen in the scanning mirror, the third  
3 focusing lens producing at its output a focus of the beam which  
4 follows a curved line that lies on the surface of the spherical  
5 convex surface, the focus maintaining a constant optical path  
6 length; and translation means coupled to the sample for  
7 translating the sample to produce a two-dimensional scan of the  
8 surface of the sample.

9 It should therefore readily be understood that many  
10 modification and variations of the present invention are possible  
11 within the purview of the claimed invention. It is therefore to  
12 be understood that, the  
13 invention may be practiced otherwise than as specifically  
14 described.

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ABSTRACT

A scanning system for scanning in first and second dimensions a desired surface topology of a sample, the scanning device comprising: a light source for producing a collimated light beam; a first scanning device responsive to the collimated light beam from the light source for producing a first scanned beam in a first dimension with a constant optical path length; and a second scanning device coupled between the first scanning device and the sample for focusing and scanning the first scanned beam in a second dimension onto the surface region of the sample to cause the collimated light beam to scan the surface topology of the sample with a constant optical path length in each of the first and second dimensions of the desired topology of the sample. In a second embodiment of the invention, a beam of light is focused by a first lens before a scanner and the scanner is rotated. Second and third lenses arranged in a 4-f combination are used to image rotated focal spots along a spherical convex surface of a sample while the optical path length stays constant. Slow scanning in other dimensions can be performed by mechanical means.

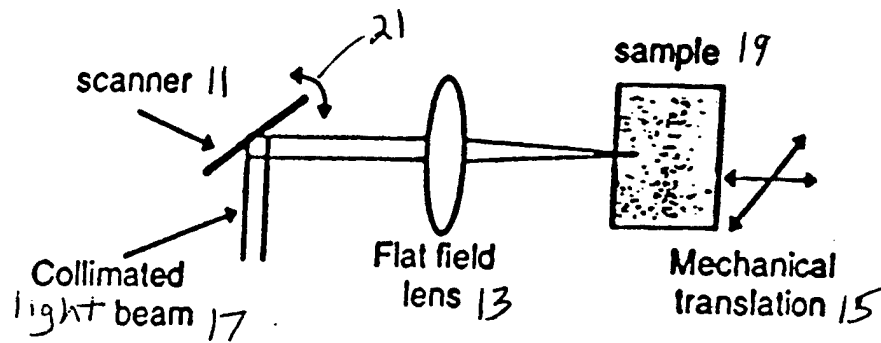


FIG. 1

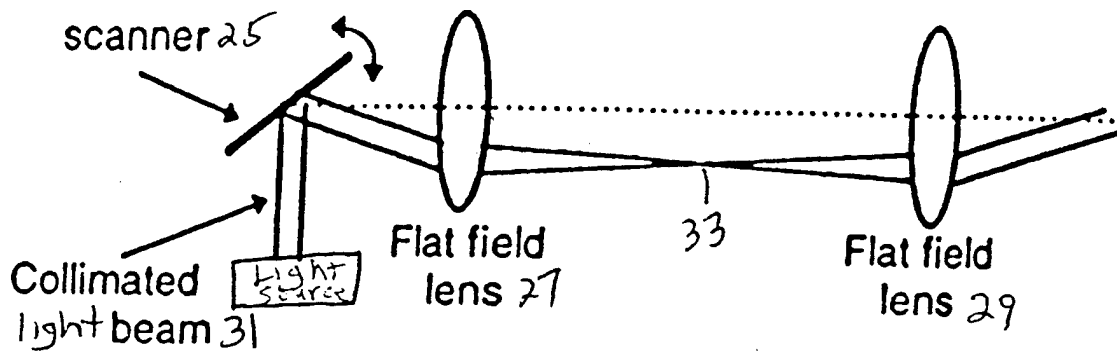


FIG. 2

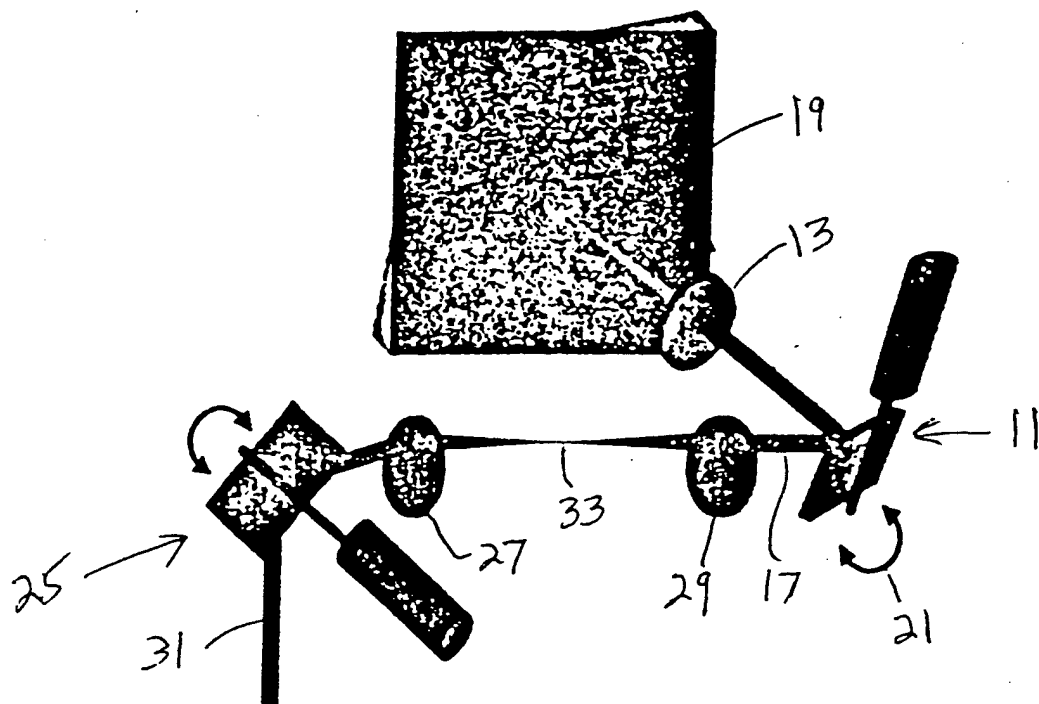


FIG. 3

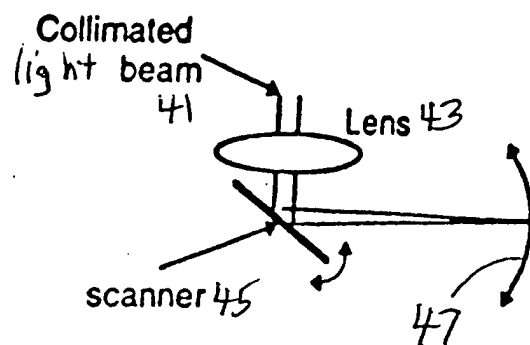


FIG. 4  
PRIOR ART

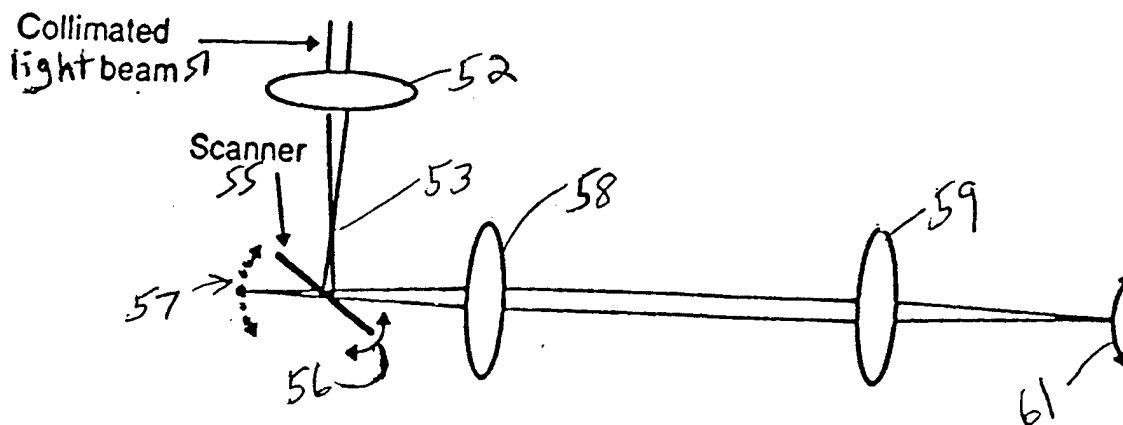


FIG. 5